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Preliminary studies of the effect of x-ray irradiation, typically used to simulate radiation effects in space, on top contract, pentacene based field effect transistors have been carried out. Threshold voltage shifts in irradiated devices are consistent with positive charge trapping in the gate dielectric and a rebound effect is observed, independent of the sign of applied electric field during irradiation. Carrier mobility variations in positive electric field biased/irradiated devices are interpreted in terms of the effects of interface-state-like defects.

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X-ray irradiation effects in top contact, pentacene based field effect transistors for space related applications

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Preliminary studies of the effect of x-ray irradiation, typically used to simulate radiation effects in space, on top contact, pentacene based field effect transistors have been carried out. Threshold voltage shifts in irradiated devices are consistent with positive charge trapping in the gate dielectric and a rebound effect is observed, independent of the sign of applied electric field during irradiation. Carrier mobility variations in positive electric field biased/irradiated devices are interpreted in terms of the effects of interface-state-like defects. © *2006 American Institute of Physics*.
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Organic semiconductor field effect devices based upon the metal-oxide-semiconductor field effect transistor (MOSFET) structure remain a tantalizing prospect for future applications in the area of flexible, lightweight, and conformal electronics. Although the carrier mobilities are significantly lower than those observed in classical, crystalline, or polycrystalline semiconductors, thus limiting the likely frequency response of organic based devices, other advantages may outweigh this in specific applications. One area in which organic electronics may hold significant promise is in very high altitude or space technology where conformality may be useful and, in particular, where weight considerations are imperative. In order for organic devices to be considered for these applications, assessment of their reliability in the presence of radiation is essential and thus far little has been reported on this subject.[1] Furthermore, it is important to note that radiation levels in space and at high altitude are such that the primary mechanism of degradation is through accumulated defect generation as opposed to macroscopic material destruction. A study of radiation effects therefore brings us directly into the realm of defects in organic semiconductors which also appears to be an area of growing interest.[2–4]

In order to begin to determine the consequences of irradiating organic based MOSFETs, we have taken the archetypical material pentacene which has been well characterized and has one of the largest known carrier mobilities. The results of these preliminary studies are reported in the following.

Dry thermal oxides were grown to a thickness of ~300 nm on degenerate n^{++} type Si wafers and the oxide surfaces were then treated in a vapor of octadecyl triethoxysilane (OTS) for 5 h at 110 °C. Following this treatment pentacene was thermally evaporated to a thickness of 100 nm onto the oxide surface held at 80 °C. Finally, Au electrodes (45 nm) were evaporated onto the pentacene surface through a shadow mask. The drain and source electrodes were 4000 μm in width with a spacing of 200 μm, giving a device channel width (Z) to length (L) ratio of 20. In order to perform irradiation and electrical characterization of these devices an Aracor 4100 system was used together with a Hewlett-Packard 4142 instrument. Devices were probed using W tips *in situ* in the irradiator. Such x-ray irradiation is typically used to simulate the effects of very energetic electron or proton radiation effects in space. For the W target in the irradiator a 50 kV accelerating voltage and a current of 5 mA gave an exposure rate of 130 rad (SiO_2) s^{-1} as measured using a Si diode. Exposures up to 500 krad (SiO_2) were accumulated and during these electric fields of ± 1 MV cm^{-1} were applied across the MOSFET gate oxide (with the source and drain contacts shorted to ground potential). Prior to and following exposure, source/drain current (I_{ds}) was measured as a function of applied gate voltage (V_{gs}) for a fixed source/drain voltage of -100 V. A typical measurement time was ~10 s including data transfer. All of the experimental curves were thus measured in the saturation regime.[5] A sequence of electrical measurements was also made in which MOSFET devices were stressed electrically in the same way and for the same times as they were during irradiation but without subjecting them to any radiation. This process was undergone in order to ascertain mobility and threshold voltage variations resulting from electrical stress alone.

The freshly prepared devices had carrier mobilities $(\mu) \sim 1$ $cm^2\,V^{-1}\,s^{-1}$ but by the time measurements were actually carried out in the irradiator μ had decreased to ~ 0.75 $cm^2\,V^{-1}\,s^{-1}$. These values were determined in the saturation regime for which[5]

$$I_{ds} = (Z/L)\mu C_{ox}(V_{gs} - V_{th})^2, \tag{1}$$

where C_{ox} is the gate oxide capacitance per cm^2 and V_{th} is the device threshold voltage. In the first instance, plots of $(I_{ds})^{1/2}$ as a function of V_{gs} were made with V_{gs} swept from 0 to -100 V in -5 V steps. The slope of this plot then yielded $[(Z/L)\mu C_{ox}]^{1/2}$ and the intercept V_{th}. This measurement has several direct advantages over the alternative linear regime measurement[5] of I_{ds} as a function of V_{ds} with V_{gs} constant. Firstly, the saturation current is independent of V_{ds} so that contact resistance[6] effects are irrelevant and secondly, distortions in the initial behavior of I_{ds} as a function of V_{ds}

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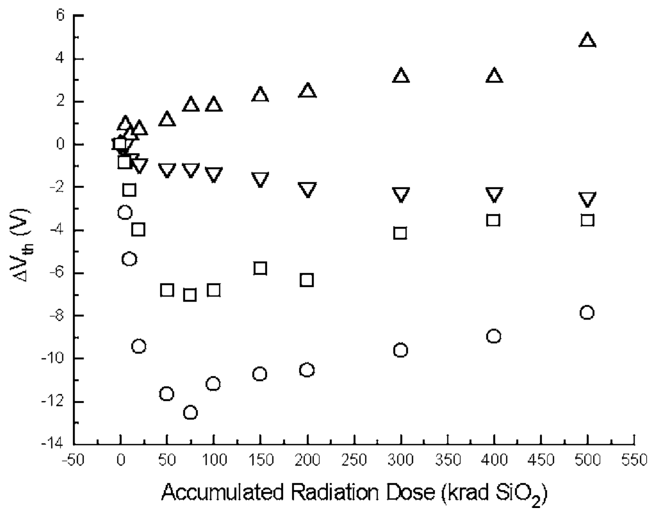

FIG. 1. Measured variation of the threshold voltage shift (ΔV_{th}) in devices subject to electrical bias stressing and electrical bias stress/x-ray irradiation. (Δ) Bias stress of 1 MV cm^{-1}, no radiation, (▽) bias stress of −1 MV cm^{-1}, no radiation (the equivalent time in seconds is given by the accumulated dose/130), (□) 1 MV cm^{-1} and irradiation, and (○) −1 MV cm^{-1} and irradiation (lower x axis for accumulated dose applies.

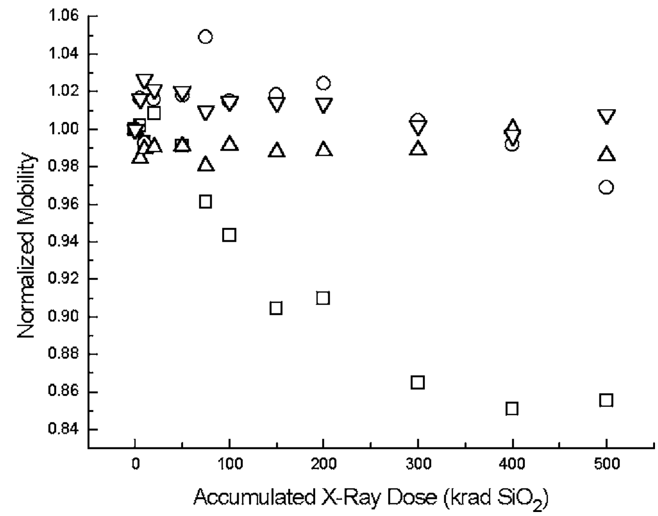

FIG. 2. Variation of the carrier mobility normalized to the prestress, preirradiation value for different devices shown in Fig. 1. (△) Bias stress of 1 MV cm^{-1}, no radiation, (▽) bias stress of −1 MV cm^{-1}, no radiation (the equivalent time in seconds is given by the accumulated dose/130), (□) 1 MV cm^{-1} and irradiation, and (○) −1 MV cm^{-1} and irradiation (lower x axis for accumulated dose applies.

resulting from electric field dependent Poole-Frenkel conduction[7] can be ignored.

The electrical bias stressing data for the threshold voltage shift (ΔV_{th}) are shown in Fig. 1, (△) for the case of a 1 MV cm^{-1} field and (▽) for the case of a −1 MV cm^{-1} field. Since we are primarily concerned with radiation effects in our measurements the x axis is shown in accumulated radiation dose in krad (SiO_2). For the electric field stress data where no radiation was used the appropriate stressing time is found by dividing the accumulated dose by the dose rate of 130 rad (SiO_2) s^{-1}. The initial threshold voltages prior to stressing or irradiation were typically in the range of −13 to −17 V. The behavior of the threshold voltage shift, at least for both positive and negative electric fields, is similar to that reported by other authors.[8] A positive variation in ΔV_{th} with time is suggestive of trapping of negative charge either in the gate oxide dielectric or in the semiconductor close to the semiconductor/dielectric interface. Similarly, negative shifts in ΔV_{th} are consistent with positive charge trapping. Given the magnitude of the electric fields applied in both positive and negative cases (small with respect to those required for Fowler-Nordheim injection, for example) it is unlikely that the observed effects result from charges in the dielectric since the potential barrier to charge injection is large. The most likely trapping site is therefore in the organic semiconductor and the data in Fig. 1 would then evidence the existence of both positive and negative charge trapping sites. It must be remembered by that the bias induced charge trapping is in addition to the substantial positive charge already present in the unstressed material or in the as-grown oxide as evidenced by the large, negative, as-made V_{th} values.

In Fig. 2, using a similar representation as for ΔV_{th}, we show the data obtained for the mobility variation as a function of applied electric field and stress time. For simplicity the mobility values are normalized to their unstressed values. Within the range of experimental error one can conclude that electrical stressing does not result in significant mobility variation at least up to ~3850 s, irrespective of the sign of the applied electric field. This result is interesting inasmuch as we concluded, from threshold voltage measurements, that bias stressing resulted in charge trapping (positive or negative) in the semiconductor close to the semiconductor/dielectric interface.

In Fig. 1 we also present the data ΔV_{th} obtained for devices subjected to electrical stress and simultaneously irradiated with x rays. For both positively (□) and negatively (○) biased devices the effect of irradiation appears to be to induce strong negative shifts of the threshold voltage shift for accumulated doses up to ~75 krad (SiO_2) followed by what appears to be a rebound effect. In order to assess what might be termed the "radiation" induced ΔV_{th} we have subtracted the ΔV_{th} values measured for bias stress alone from the values determined for devices subject to simultaneous bias stress and irradiation. The resultant curves are shown in Fig. 3. It would appear that there is still a significant negative

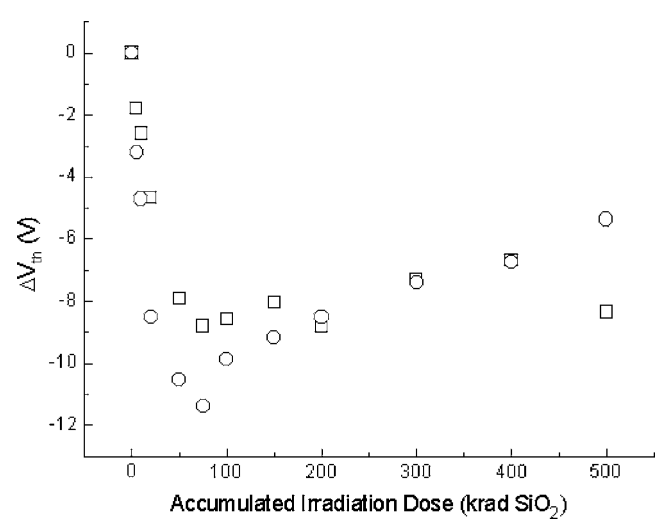

FIG. 3. Estimated variation of the threshold voltage due solely to effects of radiation deduced by subtraction: ΔV_{th} (irr)$=(\Delta V_{th})_{(\text{irradiation+bias stress})}-(\Delta V_{th})_{(\text{bias stress only})}$ (□) 1 MV cm^{-1} during stressing and stressing and irradiation, and (○) −1 MV cm^{-1} during stressing and stressing and irradiation.

voltage shift up to doses in the range of 75–100 krad (SiO_2) and the magnitudes seem to be independent of the sign of the applied bias electric field during irradiation.

In Fig. 2 we present the variation of the mobility as a function of accumulated x-ray dose. Irradiation in the presence of negative bias results in little observable variation of the mobility while irradiation in the presence of a positive bias induces a clearly visible reduction in the carrier mobility. In a classical model of reduction of mobility due to the presence of interfacial states,[9] the threshold voltage shift can be written as[10]

$$\Delta V_{\text{th}} = [q/(\alpha C_{\text{ox}})](\Delta\mu/\mu_0)/(1-\Delta\mu/\mu_0), \quad (2)$$

where q is the electronic charge, α is a processing related constant, μ_0 is the undegraded mobility, and $\Delta\mu$ is the variation in μ_0 resulting from degradation. From Fig. 2 for the positive bias/irradiated case we have $\Delta\mu/\mu_0 \sim 0.14$ for an x-ray dose of 500 krad (SiO_2) so that $\Delta V_{\text{th}} \sim -2.6 \times 10^{-12}/\alpha\, \text{cm}^2\, \text{V}$. A typical value[11] of α for Si is 2×10^{-12} cm^2 which suggests $\Delta V_{\text{th}} \sim -1.3$ V, resulting from "interfacelike" states. For the negative biased/irradiated case we have $\Delta\mu/\mu_0 \sim 0$ so there would be no associated threshold voltage shift. We note from Fig. 3 that a value of $\Delta V_{\text{th}} \sim -1.3$ V would be difficult to discern in the scatter of the data. We can therefore conclude that though significant differences occur in the behavior of the mobility when irradiated under positive or negative bias, the associated threshold voltage shifts are too small to be clearly visible in the behavior of ΔV_{th} as a function of bias and irradiation. What is perhaps important is that irradiation under positive bias appears to result in the presence of interface-state-like defects whereas all other conditions of bias stress or bias stress and irradiation do not.

The data in Fig. 3 indicate the presence of substantial threshold voltage shift due to radiation induced charges. The sign and magnitudes of the shifts, at least up to accumulated doses of ~100 krad (SiO_2), are consistent with observations of charge buildup in irradiated oxides.[12] They are usually attributed to positive charge trapping. In other oxides, rebound effects similar to those observed in Fig. 3 for doses >100 krad (SiO_2) have been attributed to the presence of negative charge trapping in oxides which compensates the effect of trapping positive charge. It must be underlined that this effect can vary significantly with the processing undergone by the thermally grown oxide so that no general statements about orders of magnitude, etc., can be made.

On the basis of the preliminary measurements reported here we are able to confirm previous measurements of positive and negative charge buildups in the organic semiconductor, resulting from electrical stressing without irradiation. The most likely locality of this trapped charge is within the semiconductor. When radiation is also present, charge trapping in the gate oxide dominates the behavior of the threshold voltage but a reduction of the mobility under positive bias and irradiation evidences the fact that there appears to be a buildup of interface-state-like defects. However, for an accumulated dose of 500 krad (SiO_2) we observed a mobility reduction of only 14% which strongly suggests that the organic devices studied here are intrinsically radiation hard and therefore potentially useful in the space environment.

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